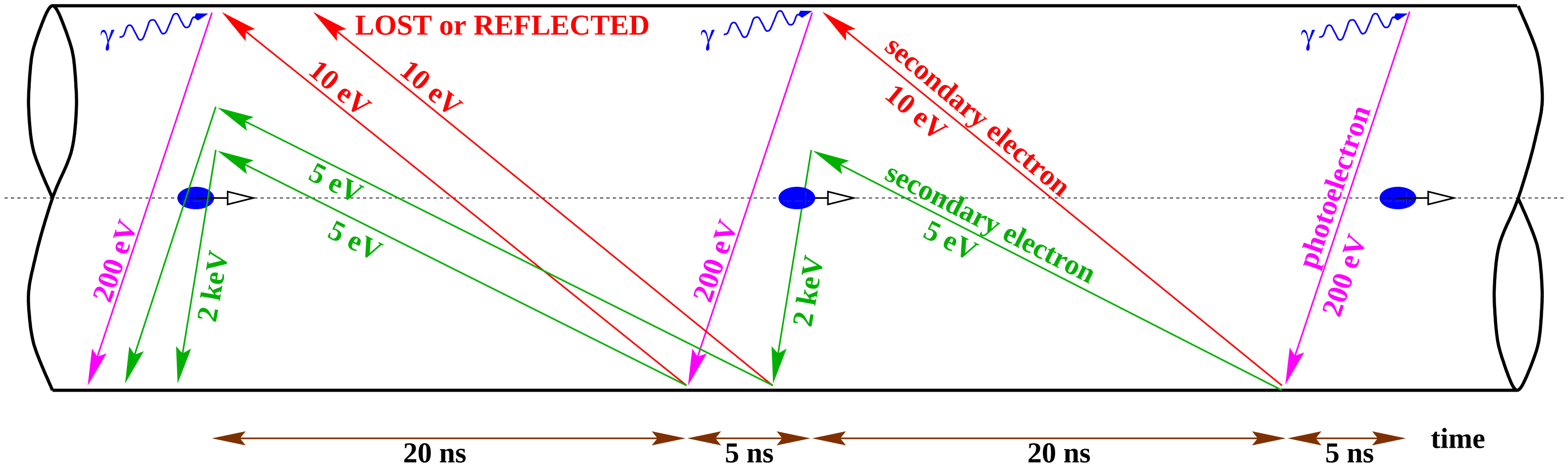
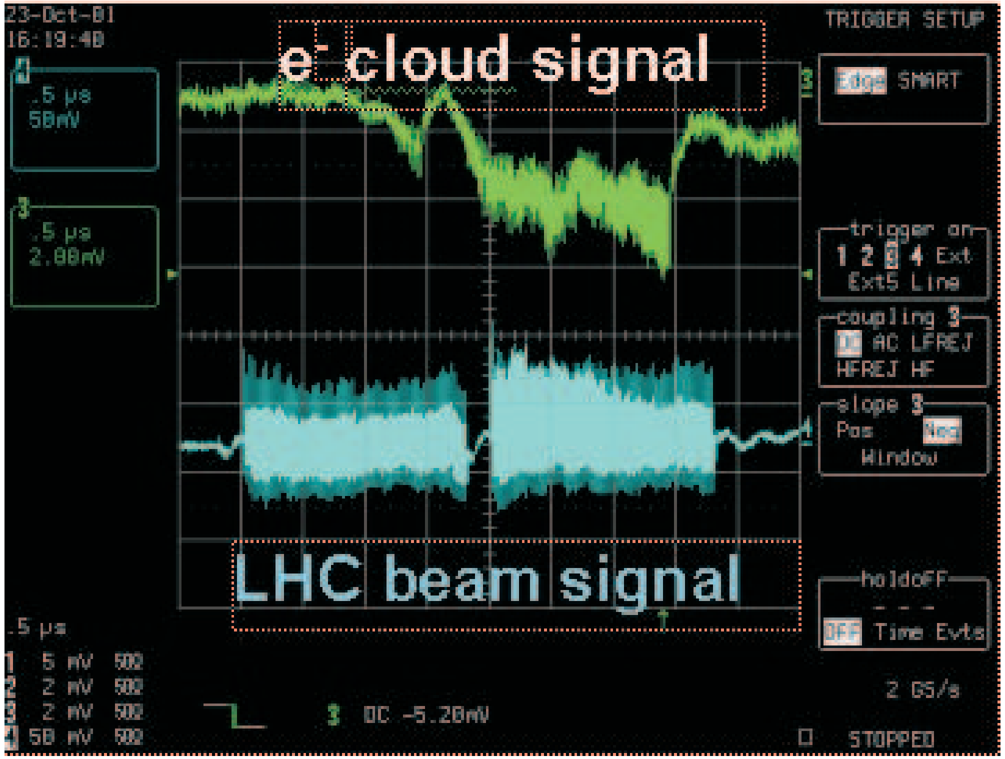
Electron Cloud Effects and LHC Concerns

- short review of electron cloud effects and cures
- some SPS observations with LHC type beam
- comparison with recent simulation results for SPS and LHC
  - electron cloud build-up (ECLOUD)
  - heat load and electron stripes
  - emittance growth (HEADTAIL)
- possible scenarios for the LHC

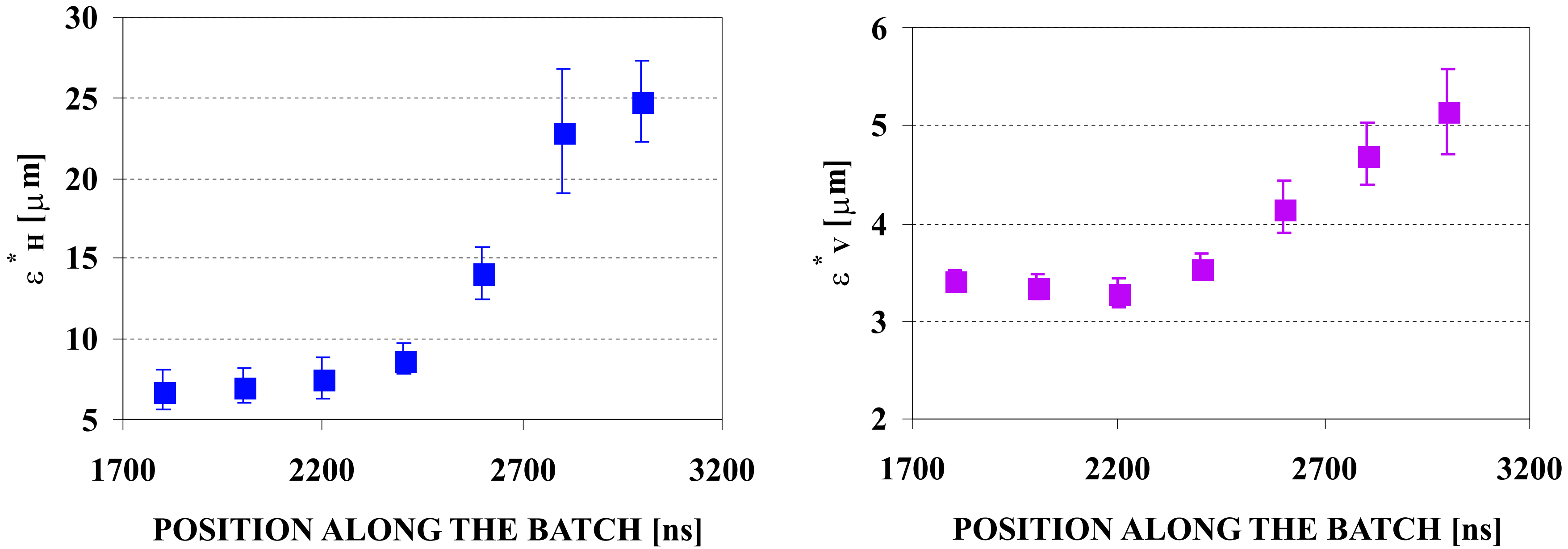


- In the LHC above 3.5 TeV, photoelectrons created at the pipe wall are accelerated by proton bunches up to 200 eV and cross the pipe in about 5 ns. Slow secondary electrons survive until the next bunch. This may lead to an electron cloud build-up with implications for *beam stability*, emittance growth, and heat load on the beam screen.
- In the LHC at 7 TeV each proton generates 10^{-3} photoelectrons/m, while in the SPS the primary yield is dominated by ionization of the residual gas and, at 20 nTorr, it is only 10^{-7} electrons/m.
- The electron cloud build-up is a non-resonant single-pass effect and may take place also in the transfer lines and in the LHC at injection.

- Electrons form a time-dependent cloud extending up to the pipe wall:
  - in field free regions this cloud is almost uniform
  - in the dipoles, electrons spiral along the magnetic field lines and tend to form two stripes at about 1 cm away from the beam axis
- Depending on the bunch spacing, a significant fraction of secondary electrons is lost in between two successive bunch passages. A minimum gain is thus required for cloud amplification and this corresponds to a critical secondary electron yield, typically around $\delta_{\rm max} = 1.3$ for nominal LHC beams
- Electron bombardment is an effective solution to reduce secondary emission. Lab measurements indicate that *the required electron dose is of* $5 \div 10\,\mathrm{mC/mm^2}$.
- Electron scrubbing in the LHC, with limited cryogenic power, may require a special proton beam with reduced intensity or increased bunch spacing, possibly with weak satellite bunches. Surface conditioning may also be possible by photon scrubbing.



Observed electron cloud build-up along LHC bunch trains at injection in the SPS for nominal train spacing of 225 ns. The bunch population is $N_b \simeq 1.1 \times 10^{11}$ p/bunch $> N_{th} \simeq 8 \times 10^{10}$ p/bunch. The time scale is 500 ns. Beam signal is delayed by about 250 ns as compared to the electron cloud signal. (Courtesy J.M. Jimenez)



Horizontal (left) and vertical (right) rms normalised emittances measured along the LHC batch (first 48 bunches) few tens of ms after injection into the SPS for a bunch intensity $N_b = 8 \times 10^{10}$ p/bunch $> N_{th} \simeq 2 \times 10^{10}$ p/bunch. (Courtesy G. Arduini)

Electron cloud induced beam instabilities

Multi-bunch instability $\qquad \frac{1}{\tau} \sim 2\pi r_{\mathrm{p}} \beta_{\mathrm{av}} c \rho_{\mathrm{el}} / \gamma$

SPS 26 GeV, $\beta_{\mathrm{av}} \simeq 40\,\mathrm{m}$, observed $\tau_{\mathrm{SPS}} \simeq 1\,\mathrm{ms}$ (50 turns)

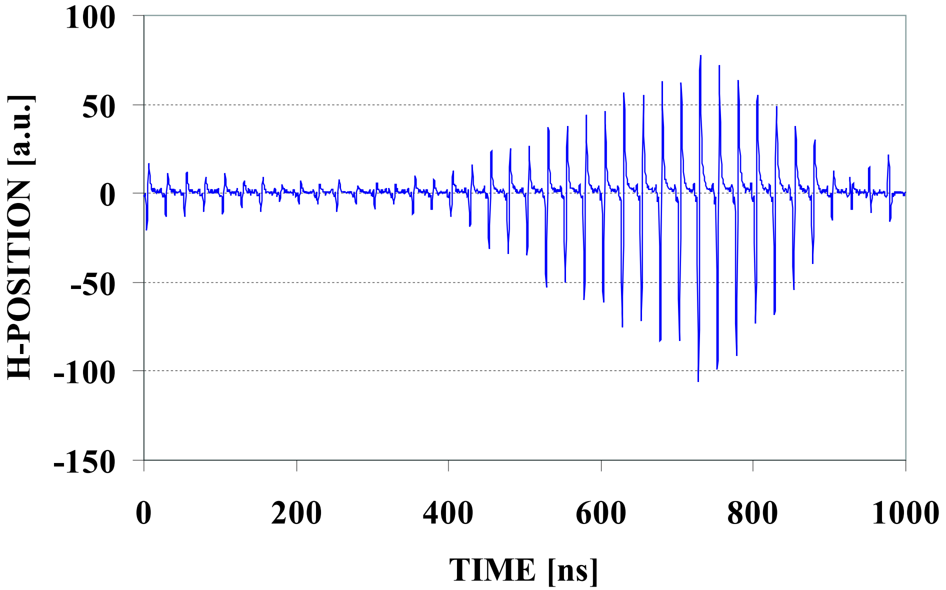
$$\Longrightarrow \rho_{\mathrm{el}} \sim 3 \times 10^{11}\,\mathrm{m}^{-3}$$

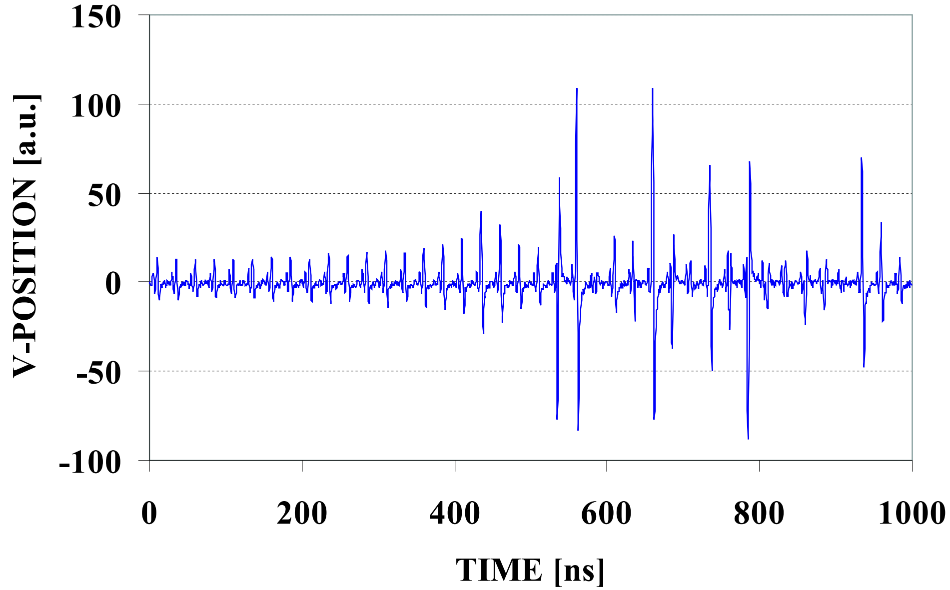
LHC 450 GeV, $\beta_{\mathrm{av}} \simeq 100\,\mathrm{m} \Longrightarrow \tau_{\mathrm{LHC}} \simeq 5\,\mathrm{ms}$ (50 turns)

Single-bunch instability (TMCI-like) $\qquad N_{th} \sim \frac{\gamma Q_s h_x h_y}{\beta av C} \frac{2 L_{\mathrm{sep}}}{r_{\mathrm{p}}}$

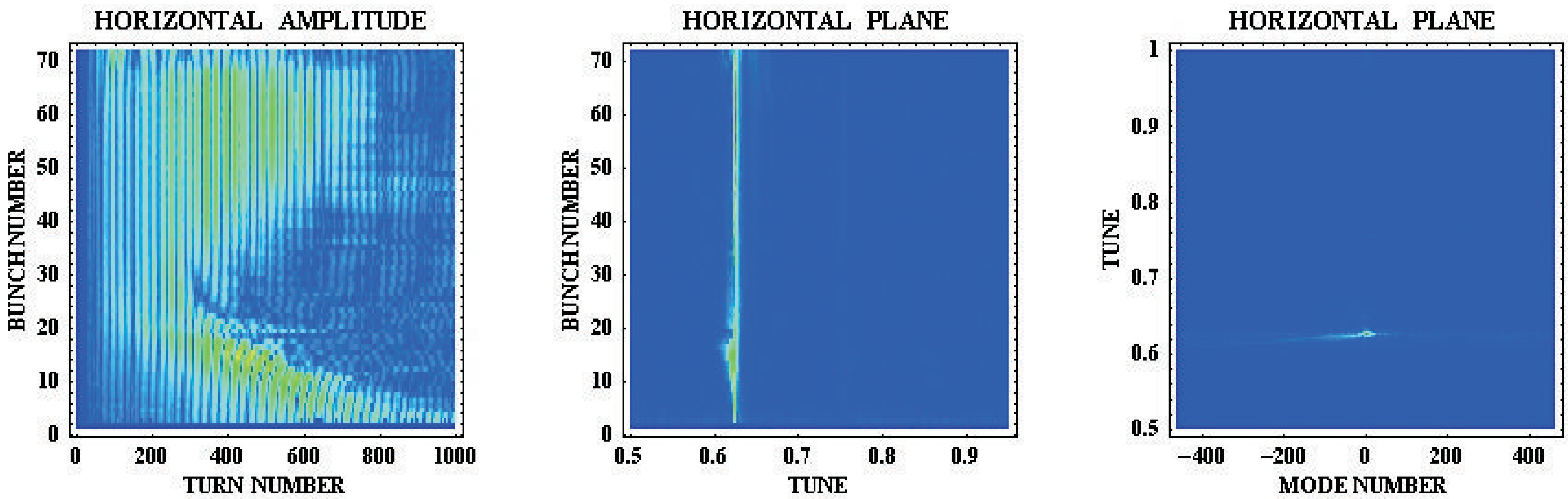
SPS 26 GeV, $Q_s = 0.003$, $C \simeq 7\,\mathrm{km}$, $L_{\mathrm{sep}} = 7.5\,\mathrm{m}$,
$h_x h_y \simeq 1.3 \times 10^{-3}\,\mathrm{m}^2 \Longrightarrow N_{th}^{\mathrm{SPS}} \sim 4 \times 10^9$ p/bunch

LHC 450 GeV, $Q_s = 0.006$, $C \simeq 27\,\mathrm{km}$, $L_{\mathrm{sep}} = 7.5\,\mathrm{m}$,
$h_x h_y \simeq 4 \times 10^{-4}\,\mathrm{m}^2 \Longrightarrow N_{th}^{\mathrm{LHC}} \sim 1 \times 10^{11}$ p/bunch

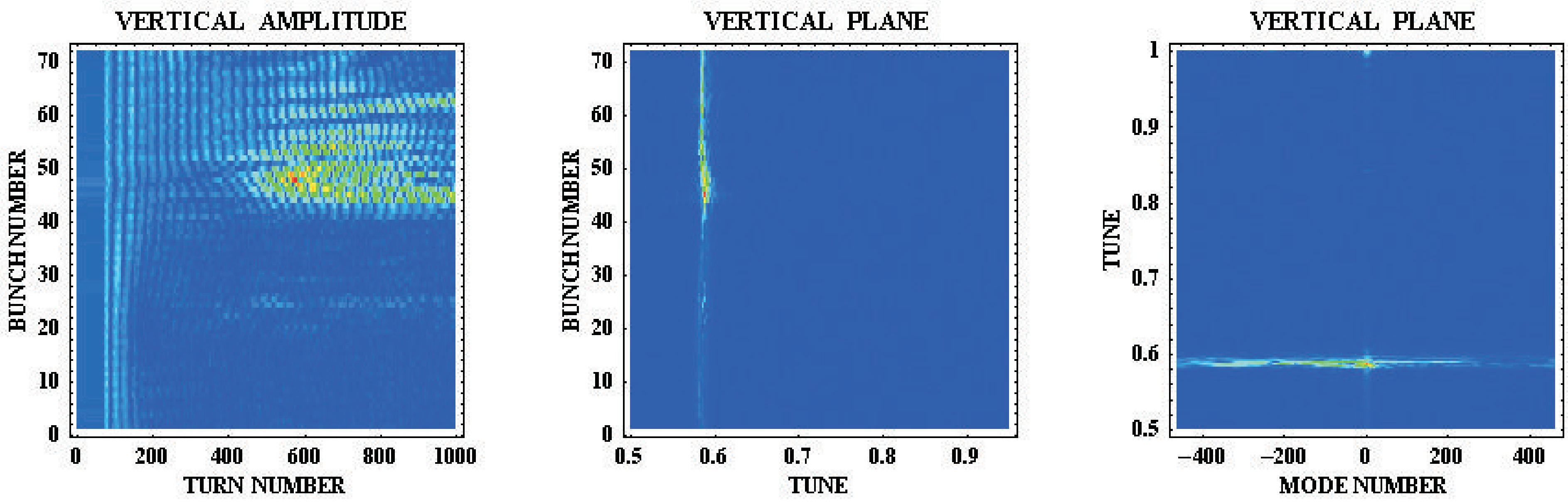




Snapshot of the transverse position for the first 48 bunches of the LHC bunch train in the SPS, measured by a wide-band strip-line coupler 60 cm long with a sampling time of 0.5 ns. A slow wave corresponding to a multi-bunch instability is visible in the horizontal plane (left), while no phase correlation exists between subsequent bunches in the vertical plane (right). (Courtesy K. Cornelis)

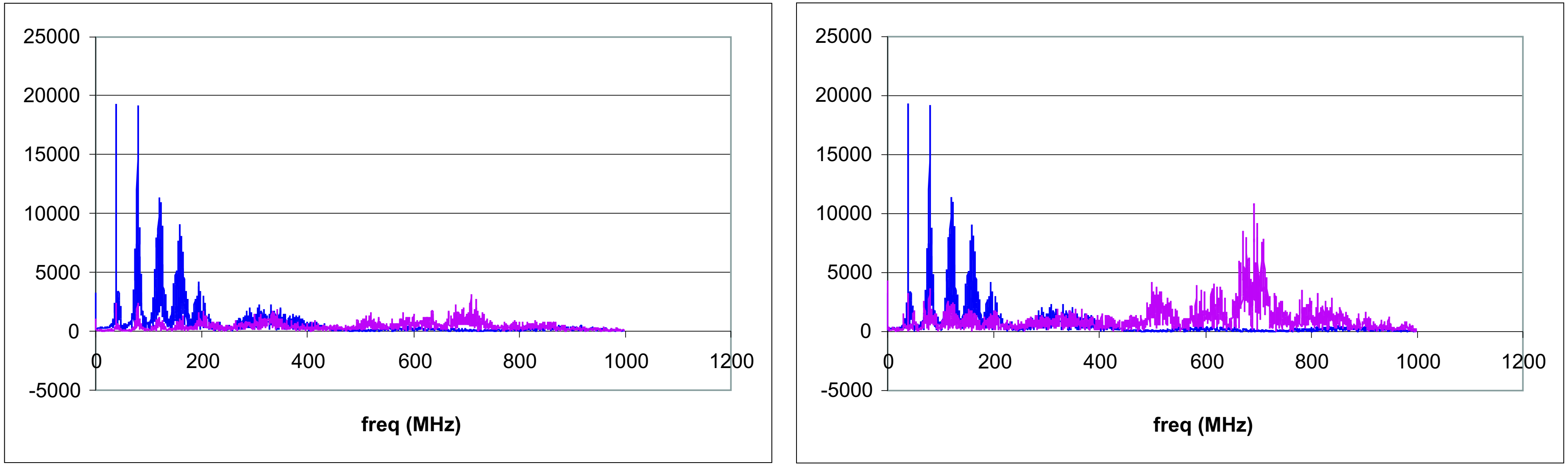


SPS before beam scrubbing: density plots of the horiz. oscillation amplitude vs. turn and bunch number (left), tune spectrum vs. bunch number (centre), tune and mode number spectra (right). Blue areas correspond to low amplitudes and red to high amplitudes. $N_b = 5 \times 10^{10}$ p/bunch $> N_{th} \simeq 2 \times 10^{10}$ p/bunch. Injection occurs at turn 30 from the start of the acquisition. (Courtesy G. Arduini)



SPS before beam scrubbing: density plots of the <u>vertical</u> oscillation amplitude vs. turn and bunch number (left), tune spectrum vs. bunch number (centre), tune and mode number spectra (right). Blue areas correspond to low amplitudes and red to high amplitudes.

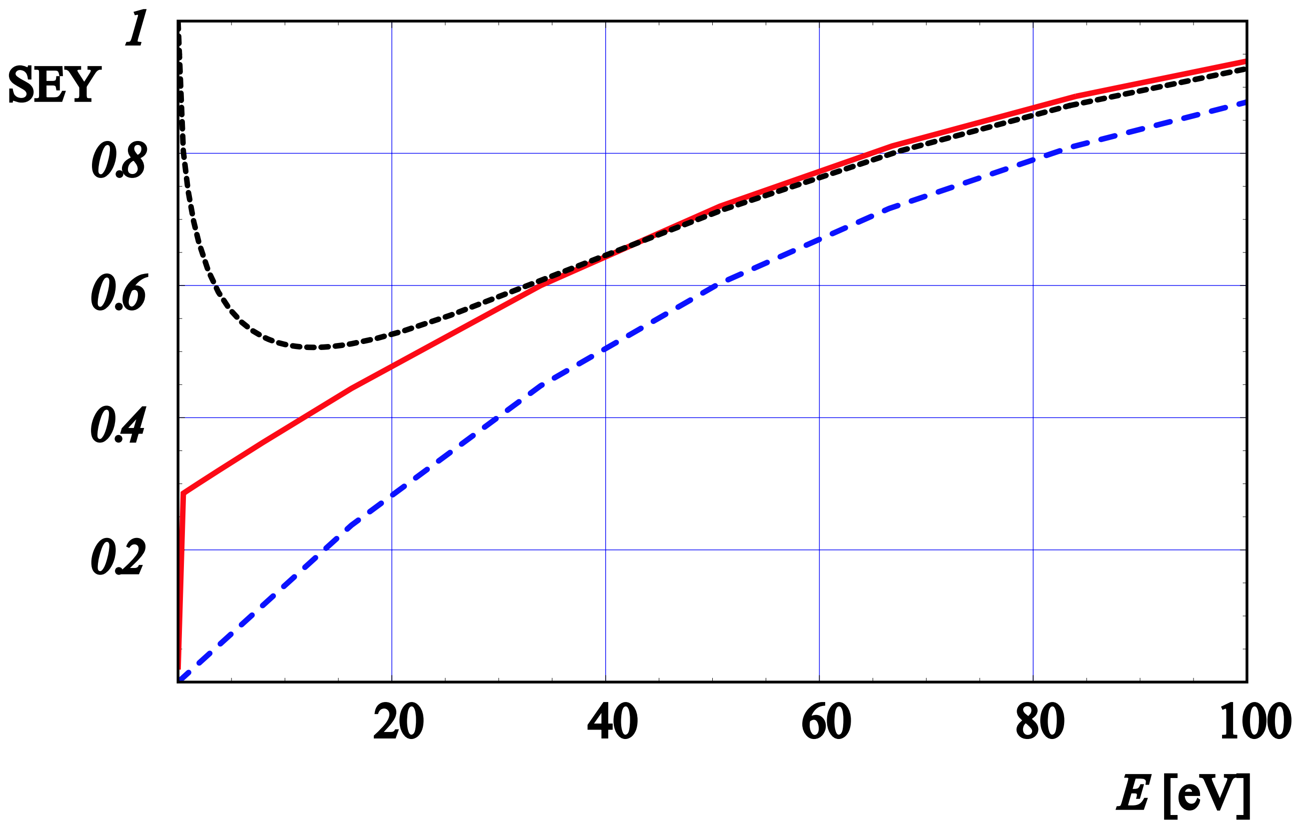
$N_b = 3 \times 10^{10}$ p/bunch $> N_{th} \simeq 2 \times 10^{10}$ p/bunch. Injection occurs at turn 71 from the start of the acquisition. (Courtesy G. Arduini)



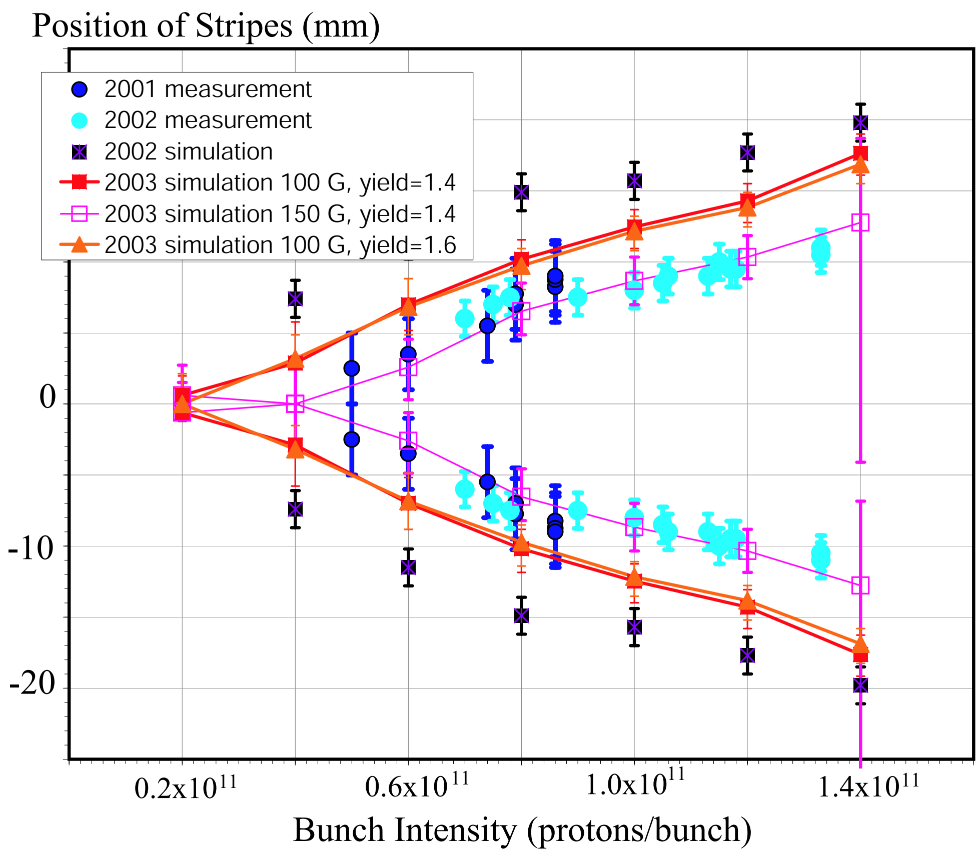
Fourier spectrum of the sum (blue) and delta (purple) signal from a wide-band strip-line monitor for the vertical plane. The oscillations of a bunch at the head (left) and at the tail (right) of the batch are compared. (Courtesy K. Cornelis)

Typical ECLOUD simulation parameters for LHC at 7 TeV.

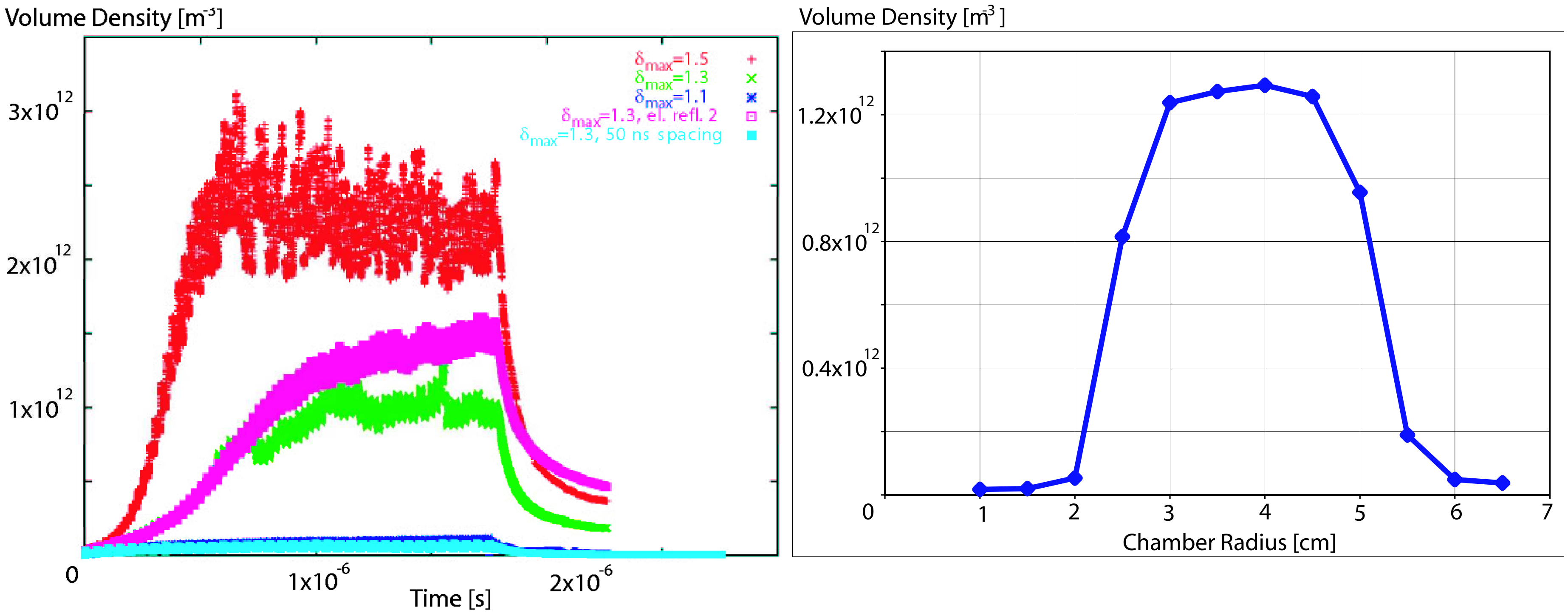
parameter	initial	final
maximum secondary emission yield δ_{max}	1.9	1.1
energy for which yield is maximum, ϵ_{max}	249 eV	230 eV
photo-electrons per absorbed photon	5%	2.5%
photo-electrons per proton and metre in the arc	0.00116	0.00058
photon reflectivity R	20%	20%
parameter for elastic electron reflection E_0	150 eV	150 eV



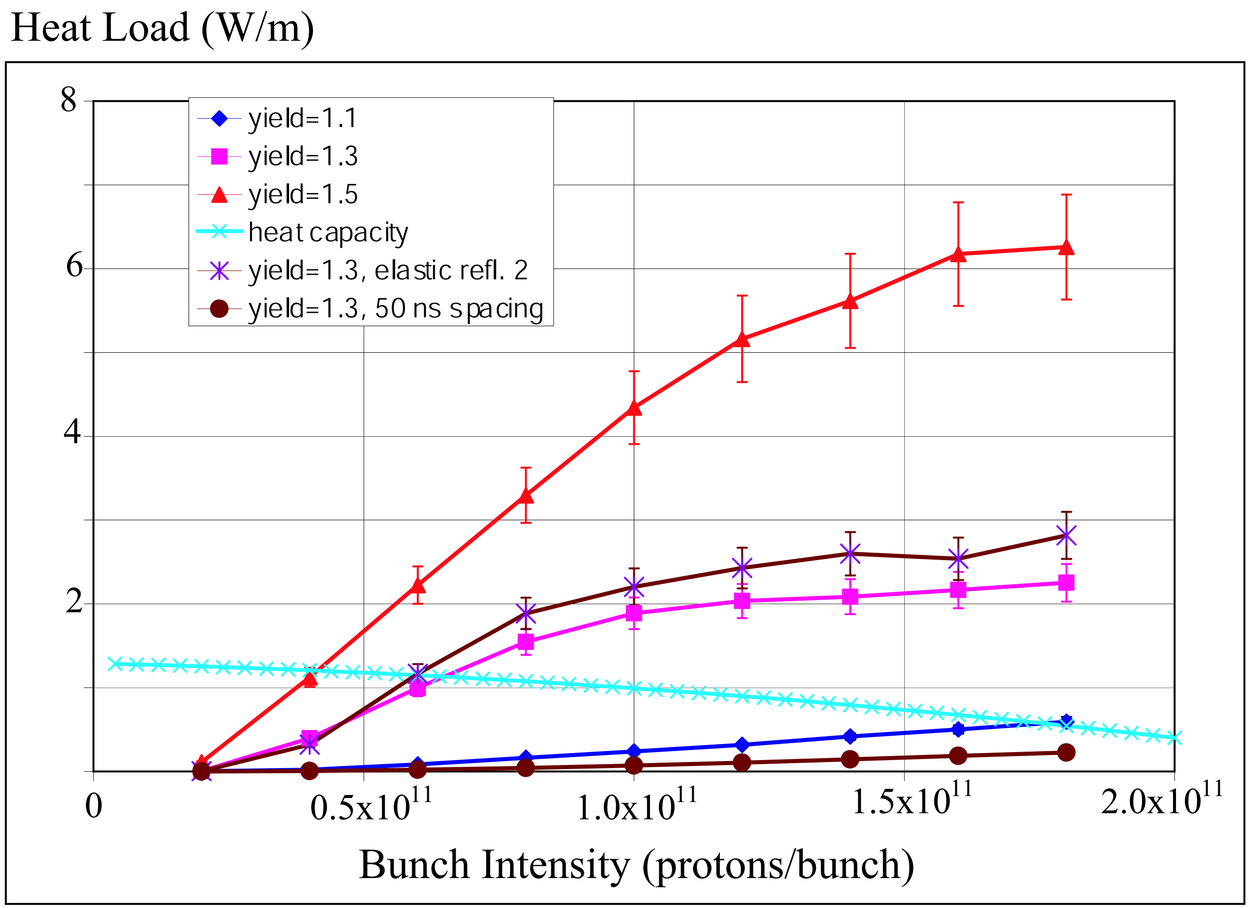
Model of the total $SEY = \delta_{\rm true} + \delta_{\rm el}$ as a function of the primary electron energy, assuming no elastic reflection (long dashes, bottom curve), a secondary emission that decreases at low energies towards about 0.3 (solid, centre curve), and the model that seems to best fit measured data (short dashes, top curve). Other parameters correspond to lab measurements of a fully scrubbed Cu surface at 9 K ($\delta_{max} = 1.06$, $E_{max} = 262\,$eV).



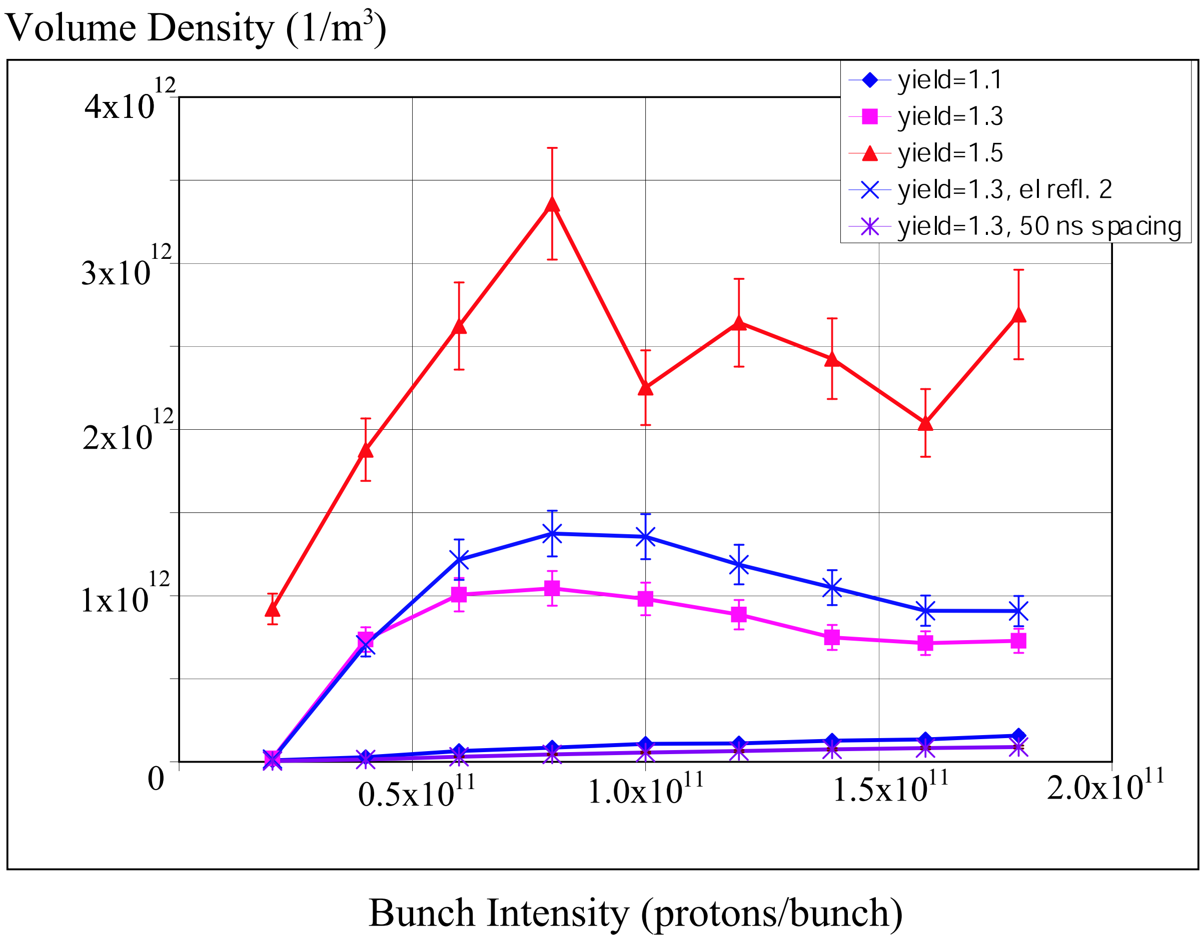
Horizontal position of regions with high electron multipacting ("stripes") measured inside a dipole magnetic field at the SPS during 2001 and 2002, vs. bunch intensity, compared with ECLOUD simulations performed in 2002 and 2003. The effects of altering the magnetic field and using different values of δ_{max} are also shown. (Courtesy M. Jimenez and F. Zimmermann)



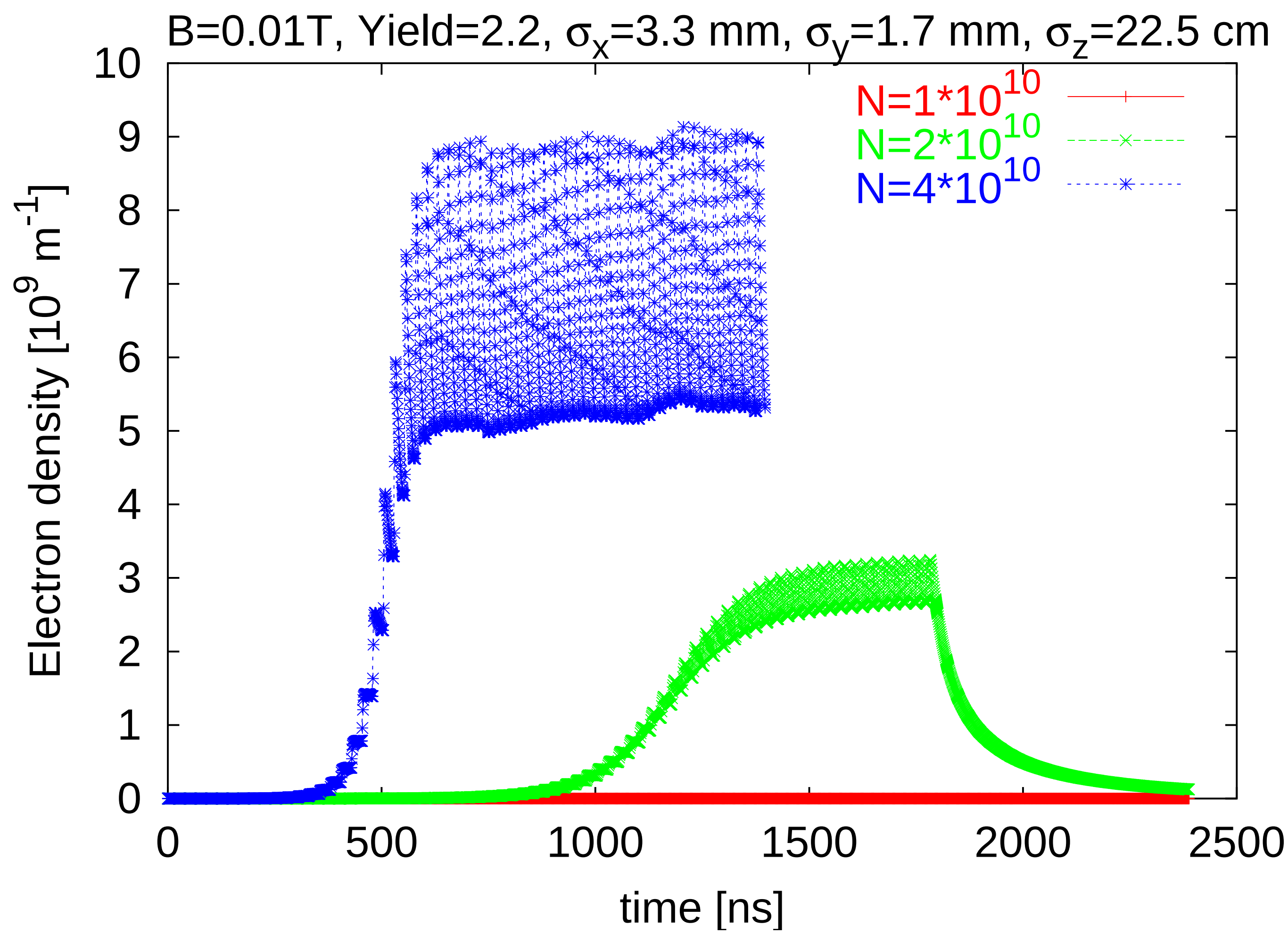
ECLOUD simulations for LHC at 7 TeV. Left: electron volume density in an arc dipole vs. time, for $N_b = 10^{11}$, various values of δ_{max}, two bunch spacings, and two models of elastic electron reflection. Right: electron density in a circular field-free region of the long LHC straight section vs. beam pipe radius, for $N_b = 1.15 \times 10^{11}$ and $\delta_{max} = 1.3$. (Courtesy F. Zimmermann)



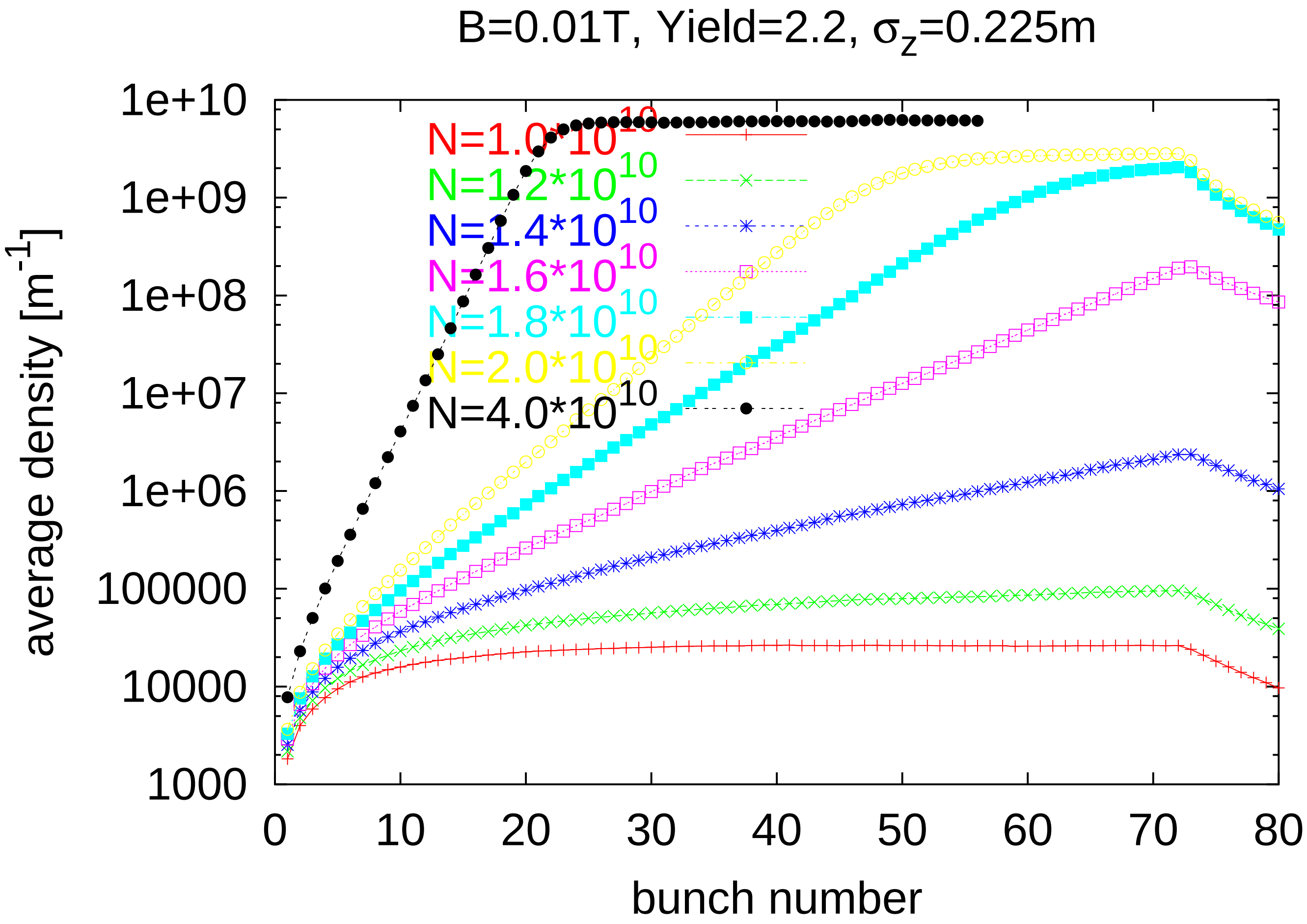
Simulated average LHC arc heat load and available beam screen cooling capacity as a function of bunch population, for $\delta_{max} = 1.1, 1.3$ and 1.5, with total or partial elastic electron reflection, and for twice the nominal bunch spacing at $\delta_{max} = 1.3$. (Courtesy F. Zimmermann)



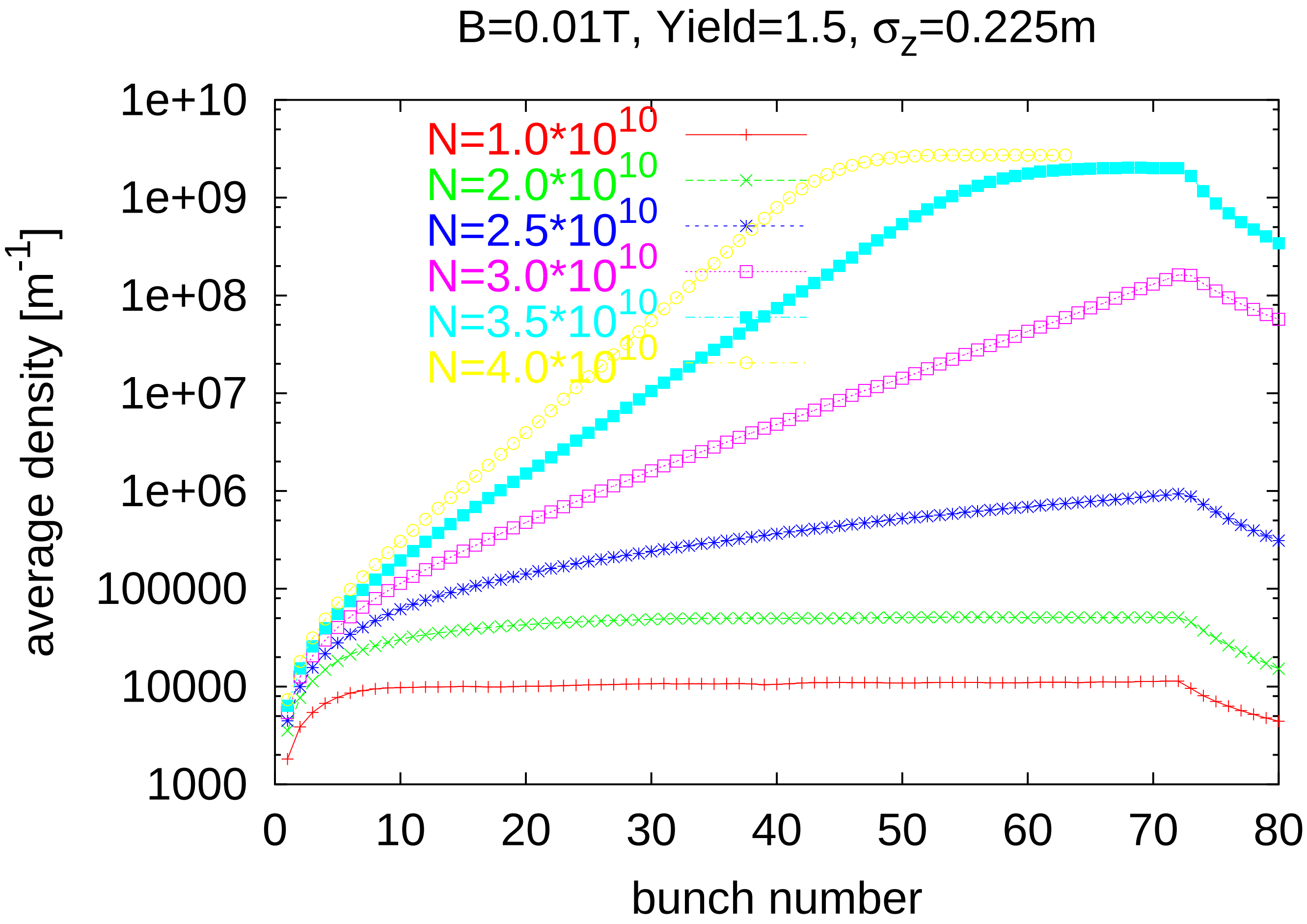
Simulated average electron volume density in the LHC arc for the last bunch in a train as a function of the bunch population, for $\delta_{max} = 1.1, 1.3$ and 1.5, with total or partial elastic electron reflection, and for twice the nominal bunch spacing at $\delta_{max} = 1.3$. (Courtesy F. Zimmermann)



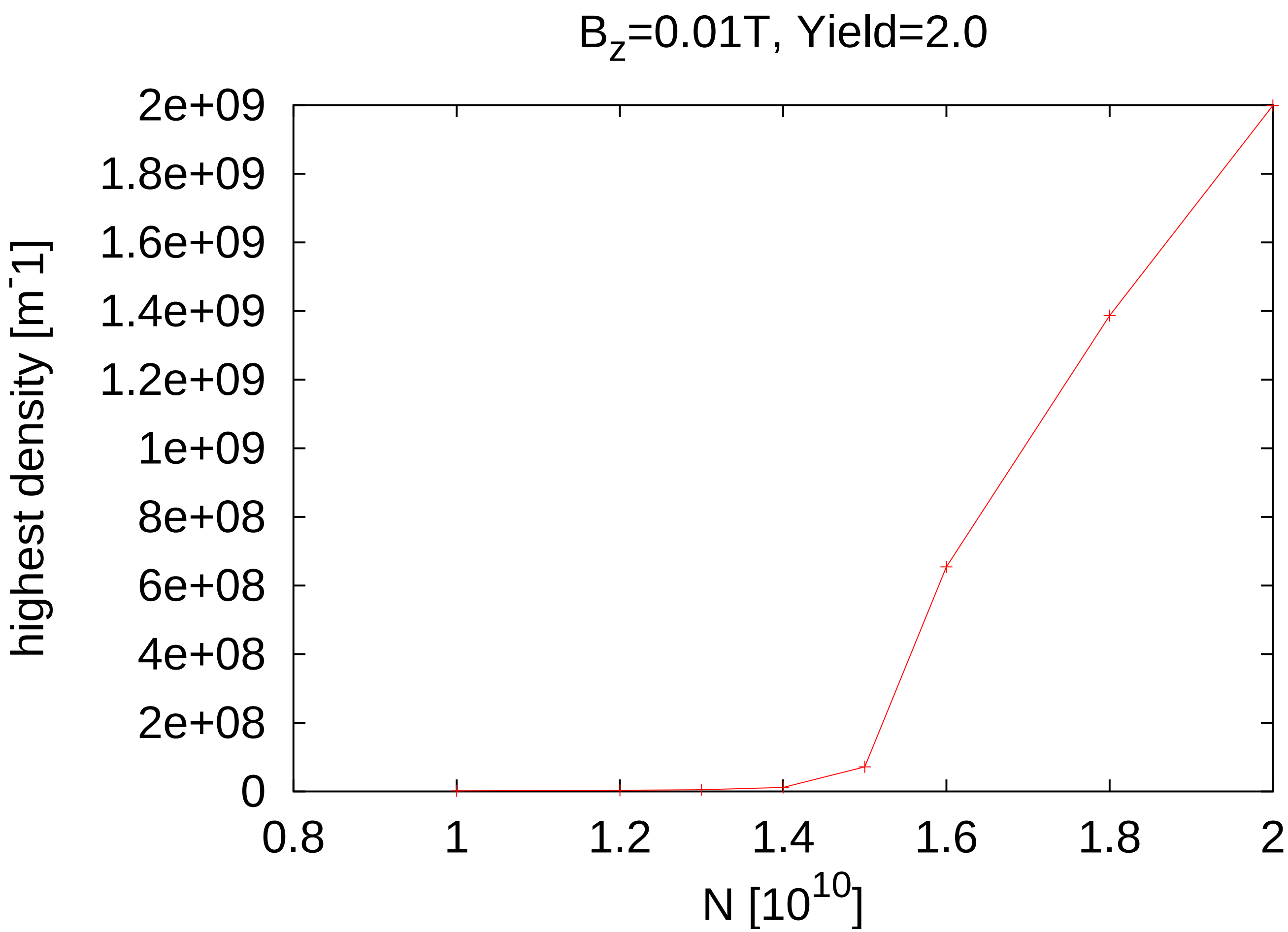
Recent simulations of electron cloud build-up at injection in the SPS for LHC type beam (72 bunches with 25 ns spacing): multipacting threshold $N_{th} \simeq 1 \div 2 \times 10^{10}$ p/bunch before scrubbing, assuming $\delta_{max} = 2.2$ and 100% electron reflection at zero energy. Elliptic chamber with 17.5 mm half-height and 76 mm half-width. (Courtesy D. Schulte)



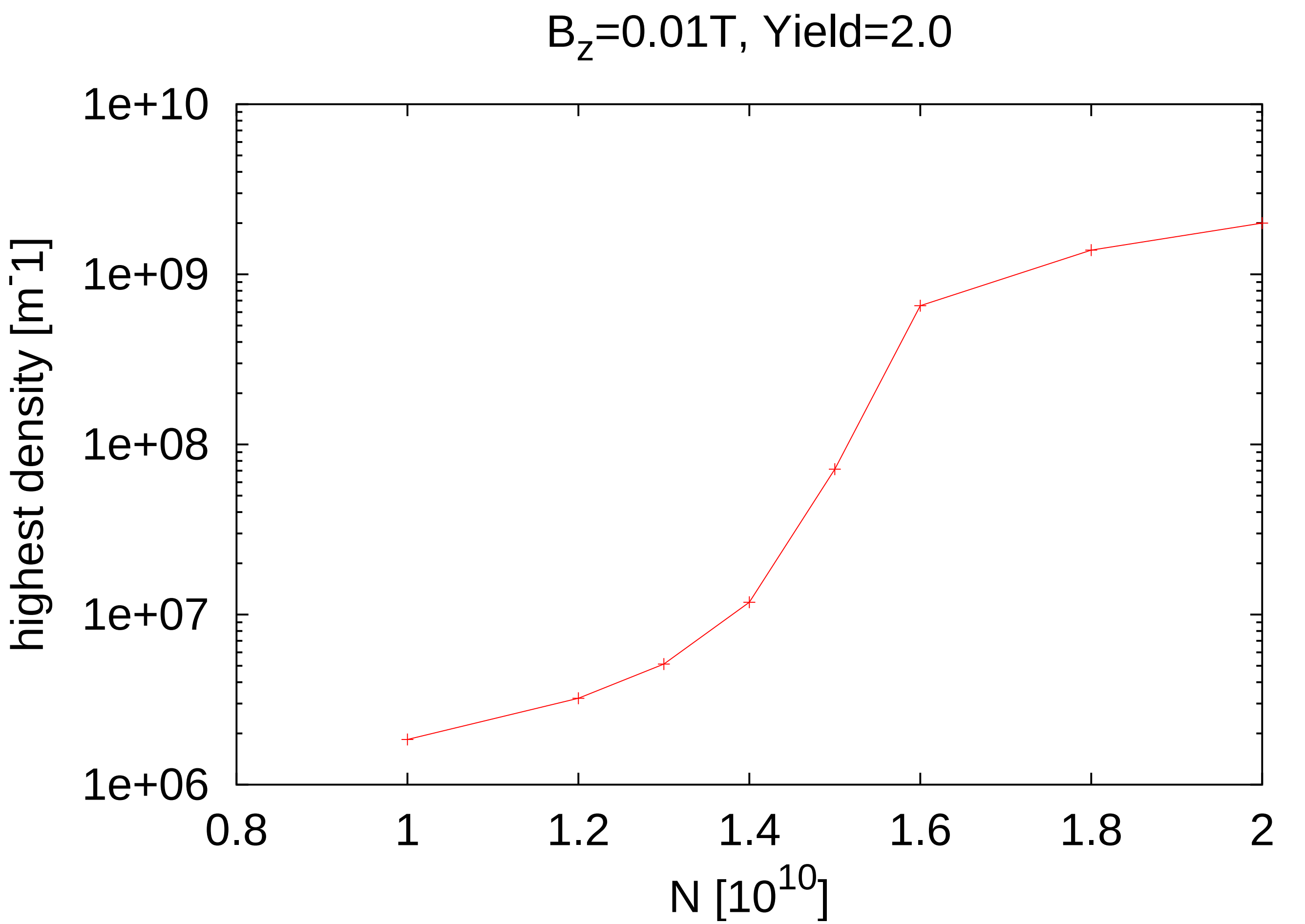
Simulated electron cloud build-up for LHC beam at injection in the SPS: average electron density (linear scale) vs. bunch number for different bunch intensities and $\delta_{max} = 2.2$. Recent simulations for 72 bunches with 25 ns spacing and elliptic chamber. (Courtesy D. Schulte)



Simulated electron cloud build-up for LHC beam at injection in the SPS: average electron density (log scale) vs. bunch number for different bunch intensities and $\delta_{max} = 2.2$. Recent simulations for 72 bunches with 25 ns spacing and elliptic chamber. (Courtesy D. Schulte)



Recent simulations of electron cloud build-up for LHC beam at injection in the SPS: highest electron density (linear scale) vs. bunch population using 3 LHC bunch trains with 25 ns bunch spacing and $\delta_{max} = 2.0$. Threshold $N_{th} \simeq 1.5 \div 1.6 \times 10^{10}$ p/bunch (Courtesy D. Schulte)



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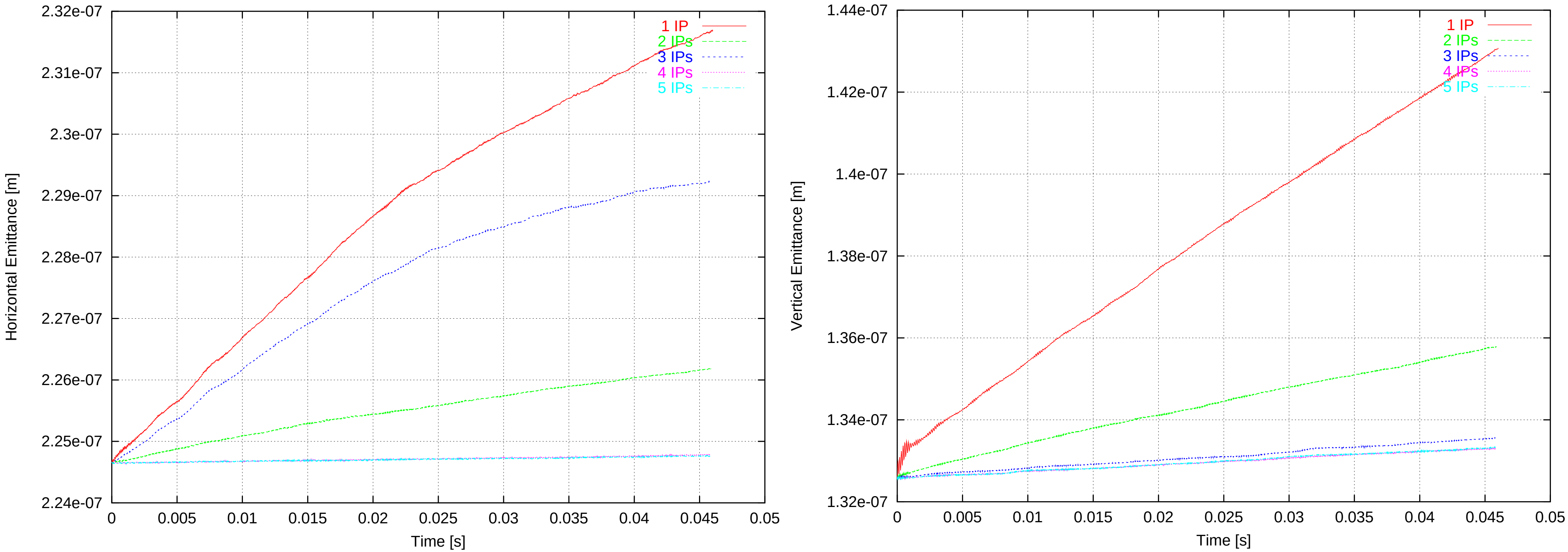
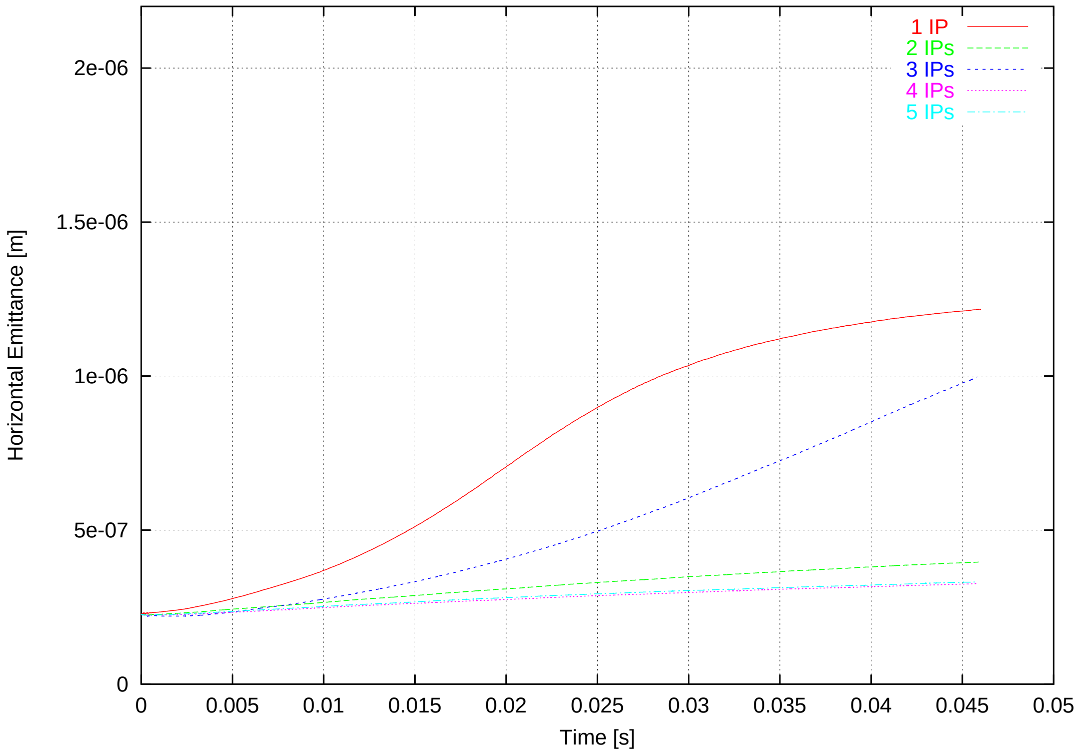
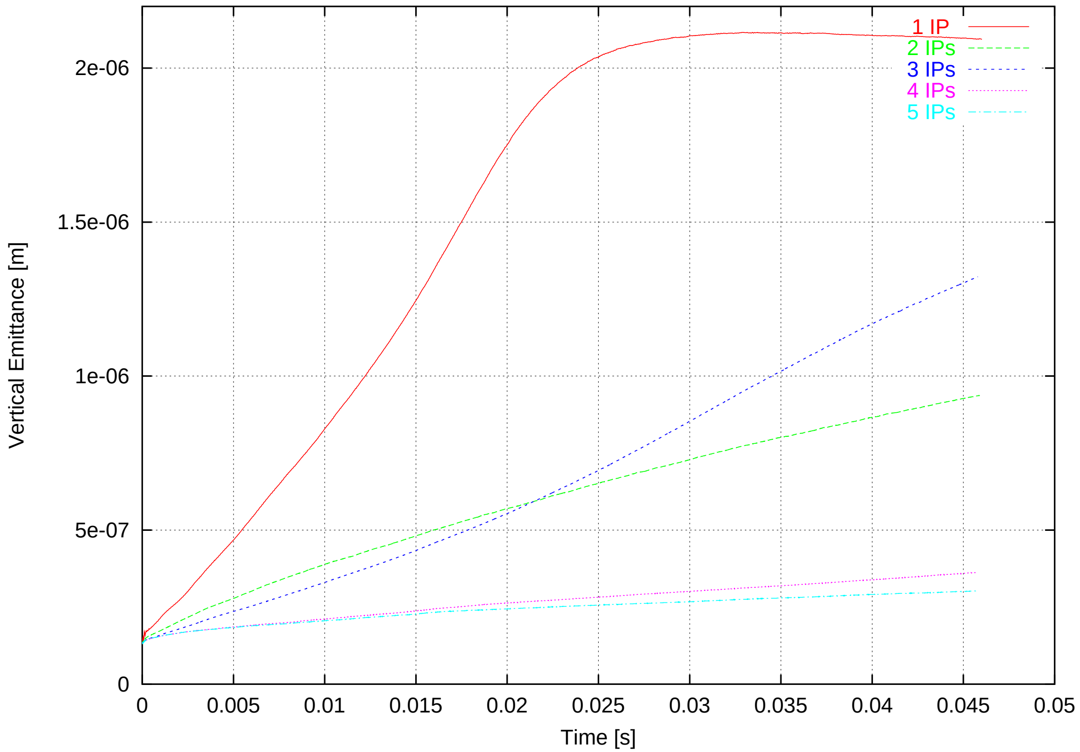
HEADTAIL simulations of emittance growth (E. Benedetto)

parameter	symbol	value
# of macro-electrons	NEL	10^5
# of macro-protons	NPR	3×10^5
# of slices	$NBIN$	70
# of grid points	N	128×128
size of the grid	σ_g	$10\sigma_{x,y} = 8.84\,\mathrm{mm}$
octupoles	no	no
boundary conditions	yes	yes
space charge	no	no
magnetic field	no	no
linear coupling	no	no
dispersion	no	no



HEADTAIL simulations of emittance growth for LHC type beam at injection in the SPS: horizontal emittance (left) and vertical emittance (right) vs. time for an electron cloud density of $10^{11}\ \mathrm{m}^{-3}$ and different numbers of beam-cloud interaction points (IPs) per revolution. Field free region, fresh cloud with uniform density generated at each IP. (Courtesy E. Benedetto)

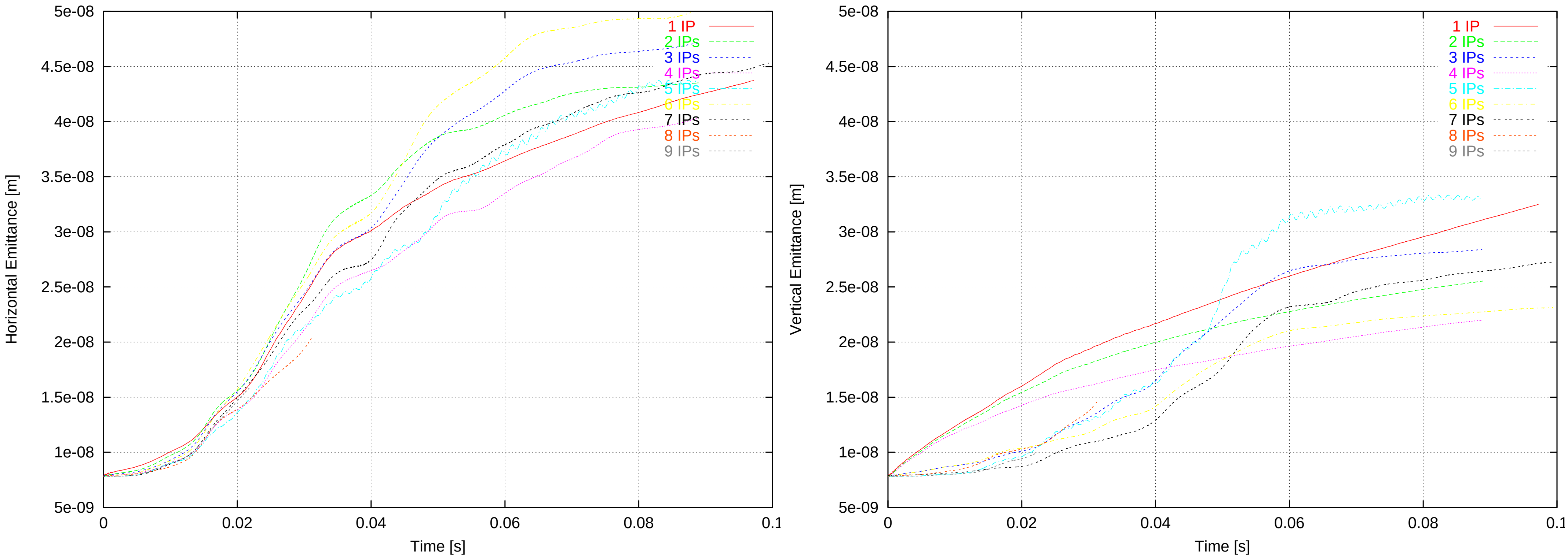




HEADTAIL simulations of emittance growth for LHC type beam at injection in the SPS: horizontal emittance (left) and vertical emittance (right) vs. time for an electron cloud density of $10^{12}\,\mathrm{m}^{-3}$ and different numbers of beam-cloud interaction points (IPs) per revolution. Field free region, fresh cloud with uniform density generated at each IP. (Courtesy E. Benedetto)

parameter	symbol	LHC	SPS
electron cloud density	ρ_e	6×10^{11} m^{-3}	10^{11} and 10^{12} m^{-3}
bunch population	N_b	1.1×10^{11}	1.1×10^{11}
beta function	$\beta_{x,y}$	100 m	40 m
rms bunch length	σ_z	0.115 m	0.3 m
rms beam size	$\sigma_{x,y}$	0.884 mm	0.003, 0.0023 mm
rms momentum spread	$\delta_{\rm rms}$	4.68×10^{-4}	0.02
synchrotron tune	Q_s	0.0059	0.004
momentum compaction factor	α_c	3.47×10^{-4}	1.856×10^{-3}
circumference	C	26659 km	6900 km
nominal tunes	$Q_{x,y}$	64.28, 59.31	26.62, 26.58
chromaticity	$Q'_{x,y}$	2, 2	2, 2
relativistic factor	γ	479.6	27.728
cavity voltage	V	$8MV$	$1MV$
cavity harmonic number	h	35640	4620

Parametres used in HEADTAIL simulations. (Courtesy E. Benedetto)



HEADTAIL simulations of emittance growth at injection in the LHC: horizontal emittance (left) and vertical emittance (right) vs. time for an electron cloud density of $6 \times 10^{11}\ \mathrm{m}^{-3}$ and different numbers of beam-cloud interaction points (IPs) per revolution. Field free region, fresh cloud with uniform density generated at each IP. (Courtesy E. Benedetto)

Some concerns for the LHC

- Is beam scrubbing a reasonably fast and effective way to reduce the SEY in cold conditions?

- Can we manage to control electron cloud effects during beam scrubbing? In particular, can we suppress
  - multi-bunch instabilities using the damper?
  - single-bunch effects at injection
    * by Landau octupoles or
    * by increasing the chromaticity up to 10-20 units, when dynamic aperture will be reduced?

- Emittance growth induced by multiple Coulomb scattering on the residual gas or by the beam-cloud interaction during beam scrubbing may require frequent machine re-fills. The SPS duty cycle with LHC type beam is currently limited by kicker heating.

3.2 Long term circulation (1)

Scrubbing run 2003

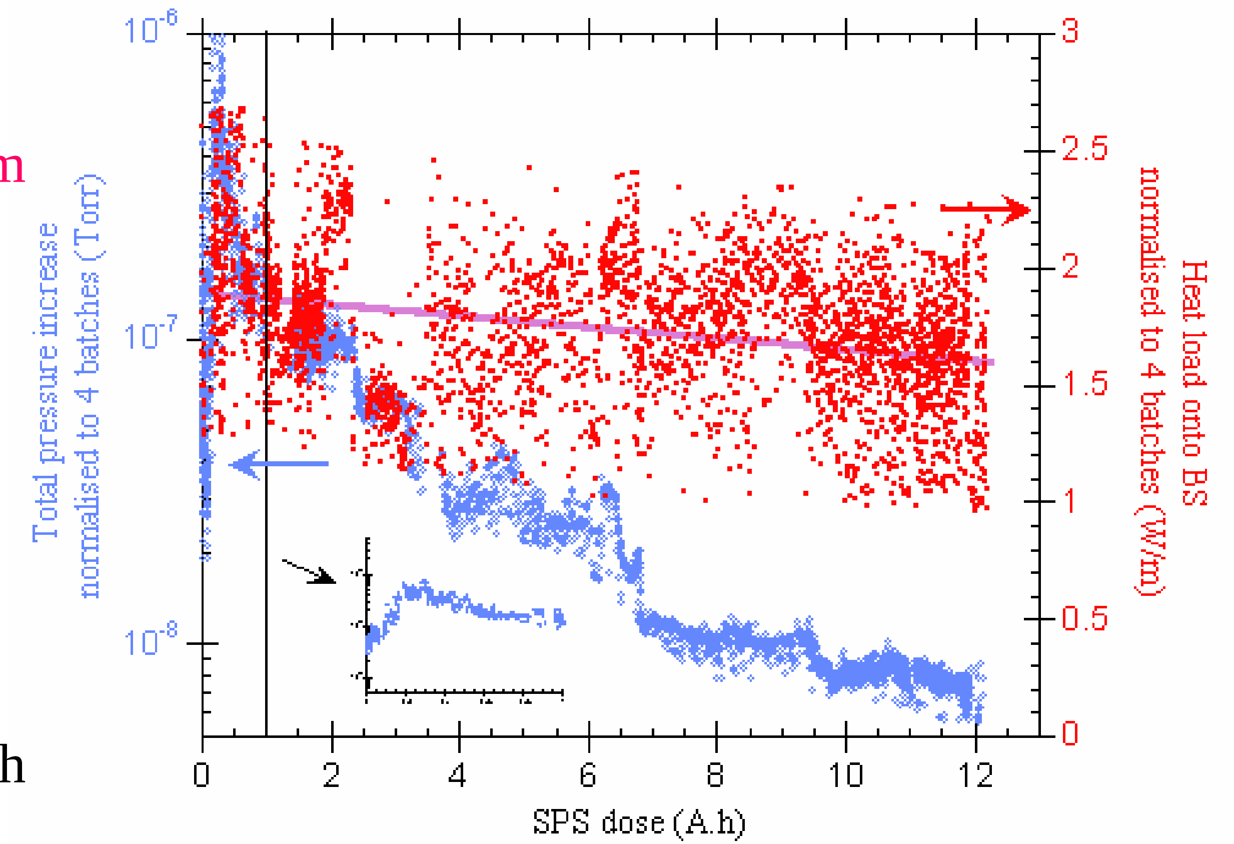
Normalised to 4 batches with ~ 1.1 10^{11} protons/bunch, 95 % duty cycle

- Initial ΔP = 5 10^{-7} Torr , final ΔP = 7 10^{-9} Torr
- A factor 70 reduction of total pressure : Vacuum cleanning

- Heat load on BS is ~ constant with electron dose, HL ~ 1.5 W/m
- HL_{final} / $HL_{initial}$ ~ 0.8 ?
- Beam conditioning ?

- I ~ 20 µA on electron shield *i.e.* I = 24 mA/m
- I_{final} / $I_{initial}$ ~ 0.7

- Dose ~ 50 mC/mm^2 for estimated <60> eV and 12 A.h



- Beam conditioning rate at 12 K << RT

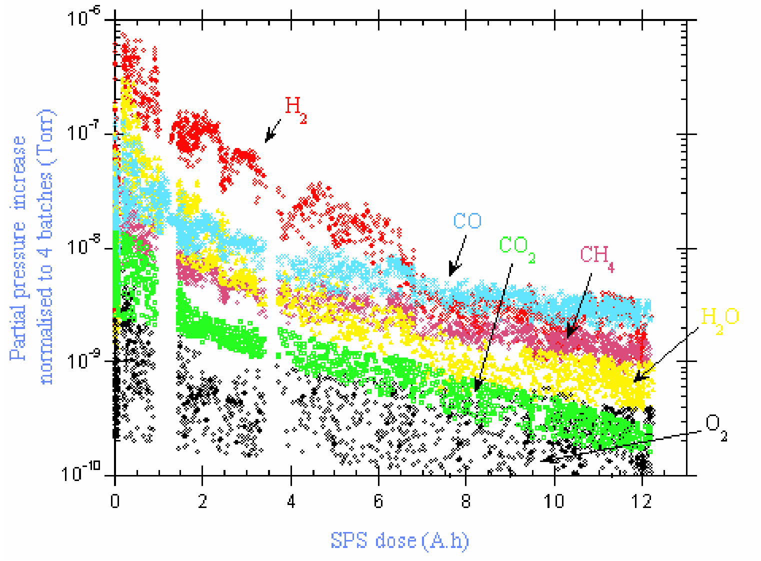
3.2 Long term circulation (2)

Scrubbing run 2003 : 12 A.h

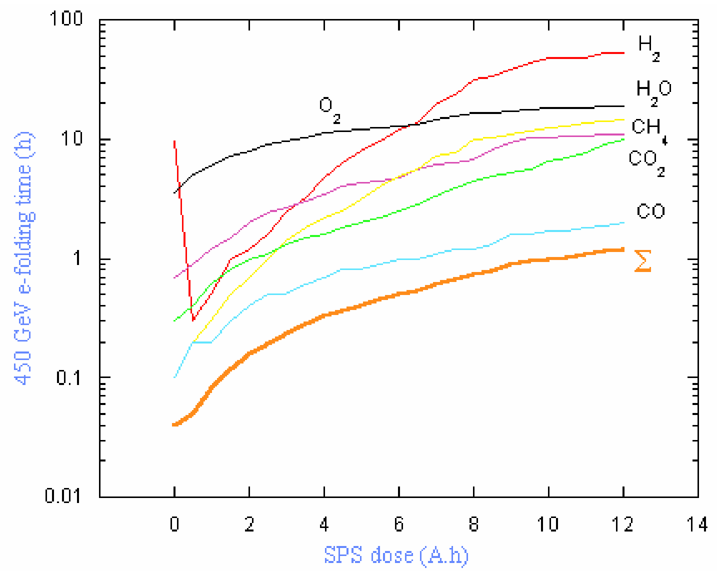
Normalised to 4 batches (0.2 A)

- Gas analysis :

  H_2 dominated turns to H_2 + CO

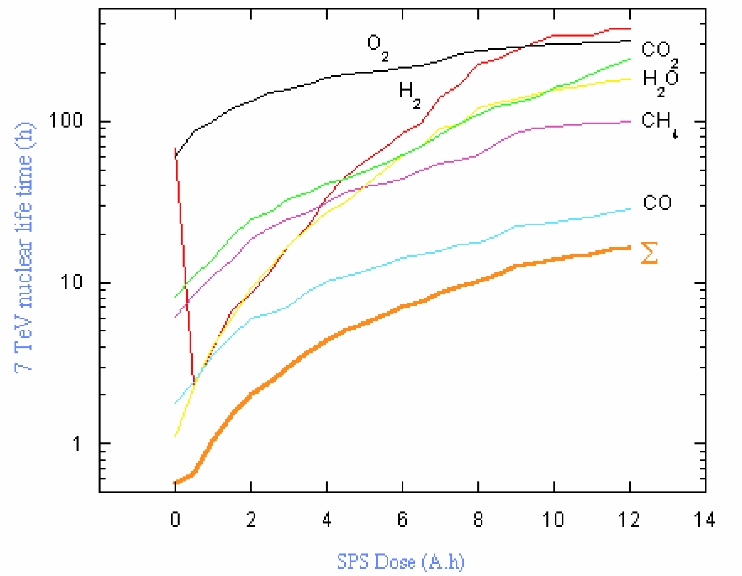


Coulomb scattering at 450 GeV



Ok to ramp (?)
But
control and decrease electron cloud power to < 1 W/m
for 40 h life time
(with 0.2 A)

Nuclear scattering at 7 TeV



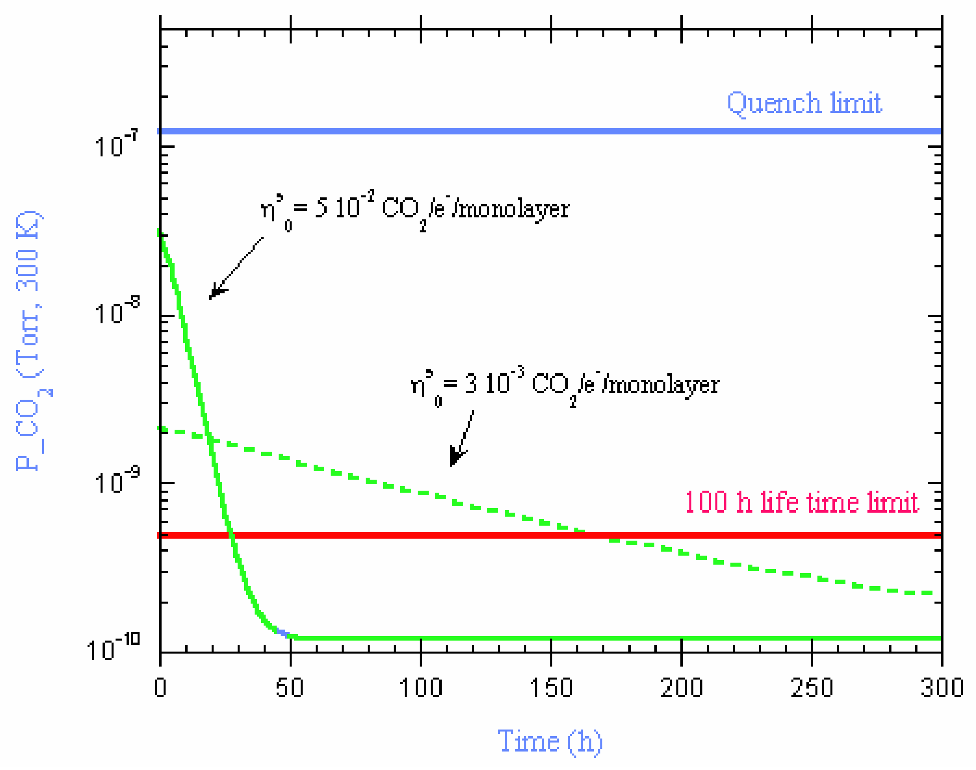
3.3 Effect of condensed gas (2)

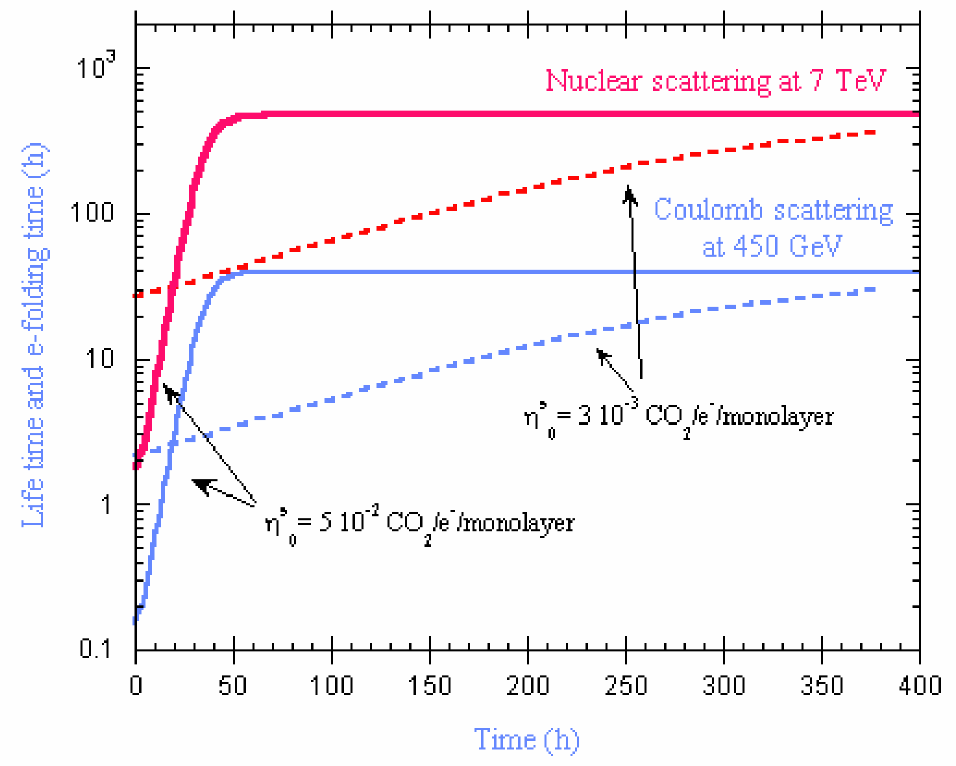
Case of condensed CO_2 onto the BS

5 10^{15} CO_2/cm^2, 1 W/m, 100 eV, LHC nominal parameters

- More than 10 h operation below 100 h life time
- Close to quench limit
- Low Coulomb scattering e-folding time

Might requires flush of CO_2





Unexpected Beam Induced Amplitude Modulation of Waveguide Modes in the SPS around 3 GHz

A strong beam induced attenuation has been observed by Fritz Caspers and Tom Kroyer for waveguide modes propagating over 30 m along the SPS beam pipe. This modulation is present even for single bunches or for beam intensities well below the threshold for electron cloud build-up. Measurements with residual gas pressures ranging from 3×10^{-9} to 1.3×10^{-8} torr gave similar results.

The beam induced attenuation shows a build up time and a memory effect of a few μs which seems to exclude mode mixing or direct beam signals, anyway very unlikely with H-modes.

Hint: Gas ionization and survival of slow electrons have time constants of μs. There may be a kind of beam induced pinch effect, which produces a very high but local electron density ($10^{16}\,\mathrm{m}^{-3}$).

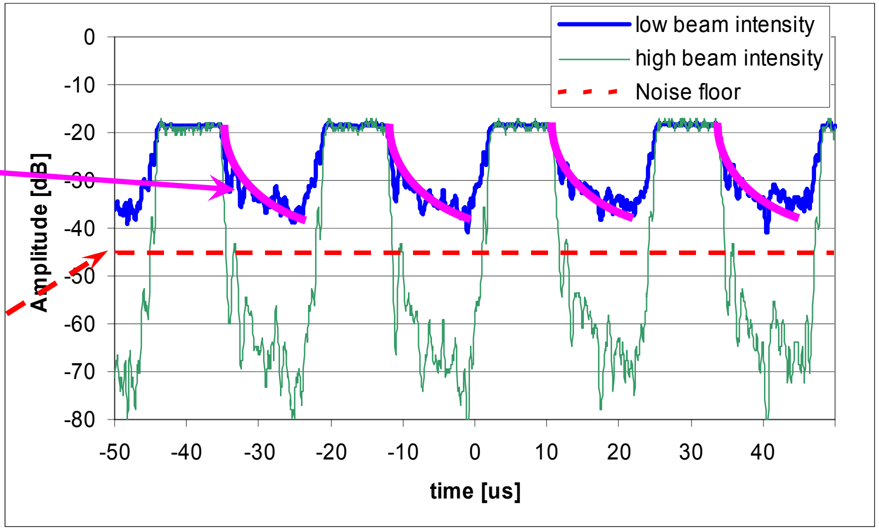
Proposal: repeat this fairly simple experiment at other machines.

Build-up time

- When we have tails, we would also expect a build-up time
- For fairly small beam we can distinguish a change in slope before reaching a kind of steady state (caution: vert. scale: dB)
- For higher attenuation we were limited by the noise floor of our instrumentation
- Is is assumed that this build-up time is always present but often masked by the general system noise floor for strong beams

Build-up time in the range of a few μs

Limitation by system noise level



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